NASA Technical Memorandum 86826

NASA-TM-86826 19860004207

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N86-13676 #

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Summary

A mathematically simple, turbulence closure model designed to treat transonic airfoil flows even with massive separation is described. Numerical solutions of the Reynolds-averaged, Navier-Stokes equations obtained with this closure model are shown to agree well with experiments over a broad range of test conditions.

Introduction

The greatest limiting factor in the accurate numerical prediction of airfoil flows has been the lack of an adequate turbulence closure model. For airfoil flows with sufficiently mild pressure gradients and no separation, simple algebraic turbulence models have been shown to yield good results. As speeds in the transonic regime and angles of attack are increased, however, adverse pressure gradients become stronger and separated flow regions make their appearance. Under these harsher conditions, the algebraic turbulence models do not do well. Such cases also present a severe test for more sophisticated turbulence models. In Ref. 1 for example, relatively poor predictions of surface pressure were obtained for a series of transonic, inviscid-viscous interaction flows (all with some separation) with both the Cebeci-Smith [2], algebraic model and the Jones-Launder [3], $k - \varepsilon$ model.

Recently (Ref. 4), a mathematically simple closure model was proposed that showed promise in treating the turbulent boundary layer development even under conditions where the inviscid-viscous interaction results in massive separation. Subsequent to this work, further evaluations of this closure model (Refs. 5 and 6) have been made using time-marching, Navier-Stokes methods.

This paper first describes the turbulence closure model of Ref. 4, and presents some of the results obtained to date with this closure model.

Closure Model

The intent of the study (described in Ref. 4) was to develop a turbulence closure model for a particular class of flows: wall-bounded shear flows subjected to large and rapidly changing streamwise pressure gradients. The impetus was the prediction of turbulent boundary layer development on airfoils under conditions of strong inviscid-viscous interaction. The model was developed under the assumption that the major difficulty encountered in the prediction of wall-bounded shear flows subjected to adverse pressure gradients sufficiently strong to cause separation has been due to the lack of (or an improper accounting of) "history effects" owing to convection.

The closure model can best be described as a hybrid eddy-viscosity/ Reynolds-shear-stress model. To account for the strong "history effects" present in flows with large and rapidly changing streamwise pressure gradients, a simplified Reynolds-shear-stress equation (an ordinary differential equation for the maximum Reynolds shear stress) is used to determine eddy-viscosity changes in the streamwise direction. Eddy-viscosity models tend to predict too rapid a change in the Reynolds shear stress when the mean flow field is rapidly distorted. The present closure model was designed to overcome this weakness.

An algebraic eddy viscosity distribution

$$\nu_t = \nu_{to}(1 - \exp - \nu_{ti}/\nu_{to}) \tag{1}$$

$$\nu_{ti} = D^2\ 0.4y(\overline{-u'v'_m})^{1/2} \tag{2}$$

$$\nu_{to} = \sigma(x) \bullet 0.0168\ u_e \delta_i^* / [1 + 5.5(y/\delta)^6] \tag{3}$$

is used to describe the variation of the Reynolds shear stress normal to the shear layer under both attached and separated flow conditions. "History effects" are taken into account through the parameter $\sigma(x)$ in Eq. (3). The streamwise distribution of this parameter is established in the solution procedure (details are given in Ref. 5) to give a streamwise distribution of $\overline{-u'v'}$ which satisfies the following ordinary differential equation:

$$\bar{u}_m \frac{d\tau_m}{dx} = \frac{a_1}{L_m} \tau_m \left[\left(\tau_{eq}\Big|_m \right)^{1/2} - \tau_m^{1/2} \right] - a_1 \mathcal{D}_m \tag{4}$$

In this equation, τ is used to represent $-\overline{u'v'}$, which, for convenience, will be referred to as the Reynolds shear stress. The subscript m and vertical slash m denote that the quantity is evaluated at y_m, the y location where $-\overline{u'v'}$ is a maximum. This equation which describes the development of the Reynolds shear stress along the path of maximum kinetic energy is obtained from the turbulence kinetic energy equation. In Eq. (4), $a_1 = -\overline{u'v'}_m/k_m$ (where k is the turbulence kinetic energy) and is assumed to be a constant. L_m is the dissipation length scale, which is modeled algebraically. $\mathcal{D}_m$ is the turbulent diffusion and τ_{eq} is the Reynolds shear stress based on the eddy viscosity given by Eqs. (1)-(3) with $\sigma(x)$ equal to unity. $\mathcal{D}_m$ is assumed to always be positive and to depend on the nonequilibrium state of the flow (i.e., the degree $\sigma(x)$ deviates from unity). The modeled form of this term and its formulation can be found in Ref. 5. When the convective term in Eq. (4), $\bar{u}_m d\tau_m/dx$ becomes small, $\sigma(x)$ approaches unity and τ_m approaches $\tau_{eq}\Big|_m$.

Results

Results are now presented which demonstrate the present closure model's ability to describe wall-bounded shear flows over a range of conditions. All of the test cases to be presented have some separated flow; most have massive separation zones.

The first flow to be considered is the low-speed diffuser flow of Ref. 7. In Fig. 1, mean velocity profiles predicted with the present closure model and the Cebeci-Smith model are compared with the experimental measurements. These predictions were obtained with an inverse-boundary-layer method. Figure 1 illustrates the basic inadequacy of the (equilibrium) Cebeci-Smith model in predicting separated flows, and the improvements achievable with the present simple nonequilibrium model. The different characteristic shapes of the mean velocity profiles predicted by these two closure models are primarily a result of the eddy viscosity expressions used for the inner part of the boundary layer. The present closure model also did much better than the Cebeci-Smith model in predicting the surface pressure distribution (Ref. 4).

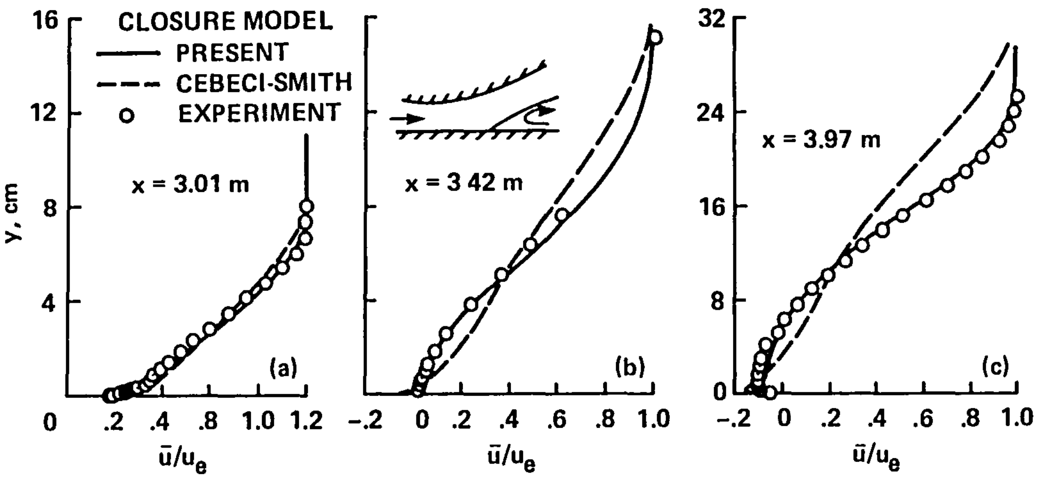

Fig.1. Mean-velocity comparisons for the low-speed diffuser of Simpson et al. [7] a) Upstream of separation; b) at separation; c) downstream of separation.

The remaining examples are all for transonic conditions. The first of these is the flow developed around an axisymmetric bump (Ref. 8). In Fig. 2, experimental surface pressure distributions for three freestream Mach numbers (M_∞ = 0.6, 0.875, and 0.925) are compared with computed distributions obtained with three different closure models. The experimental separation and reattachment locations are also shown in this figure. The computations were obtained with a computer code based on MacCormack's [9] explicit-implicit algorithm. The numerical details can be found in Refs. 1 and 5. As evident from Fig. 2, the pressure distributions obtained with the present model are in much better agreement with experiment than those obtained with either the Cebeci-Smith or Jones-Launder model.

The predicted mean velocity and Reynolds shear stress profiles for M_∞ = 0.875 based on the present model are compared to experiment in Figs. 3 and 4. At the stations x/c = 0.69 to 0.94, the calculated results are for stations slightly upstream of the experimental stations. This shift was applied to approximately account for the predicted shock location being 0.02 chord forward of the experiment. The Reynolds shear stresses are compared in shear-layer coordinates. The importance of comparing in shear-layer coordinates when the flow is highly nonisotropic and the closure model is capable of describing the Reynolds shear stresses accurately but not the Reynolds normal stresses is discussed in Ref. 5.

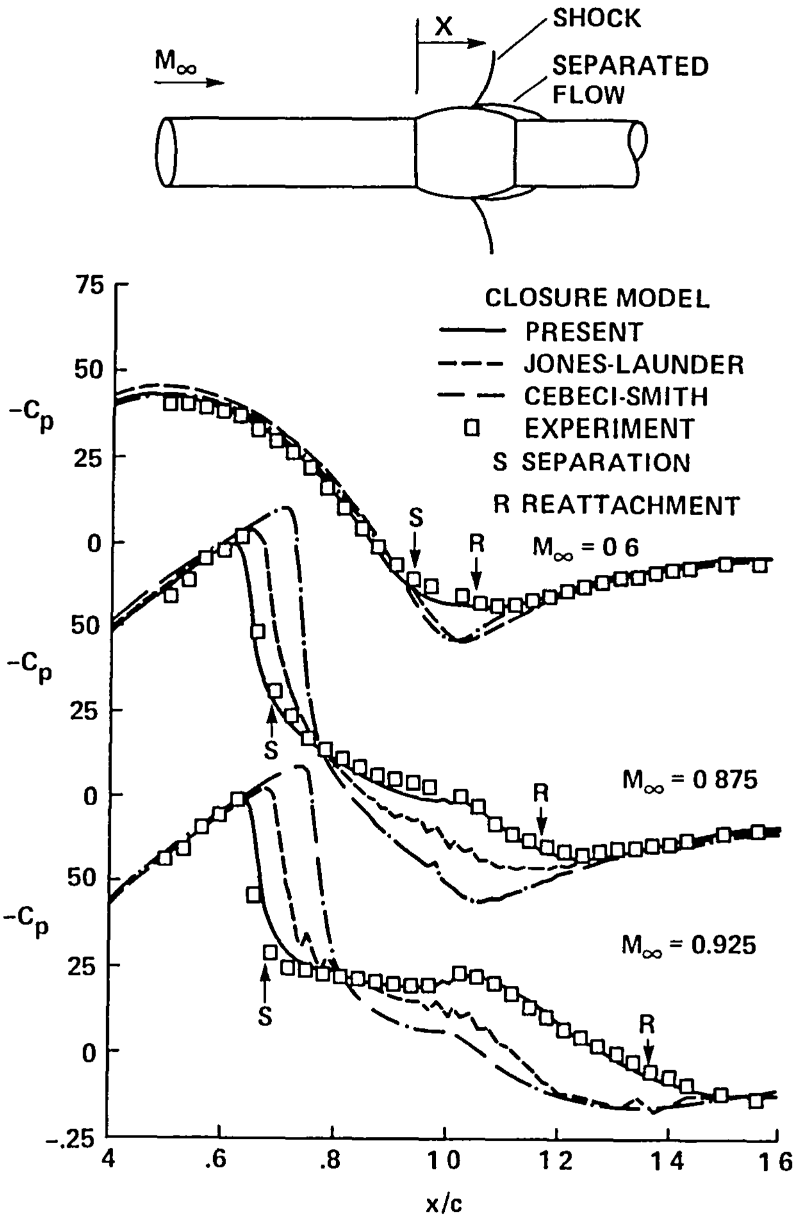

Fig.2. Surface pressure comparisons for the axisymmetric-bump flow of Bachalo and Johnson [8].

The mean velocity and Reynolds shear stress profiles predicted by the Cebeci-Smith and Jones-Launder models (not shown here) do not agree nearly as well with the experimental results (Ref. 5). Both of these models predicted more rapid rises in the Reynolds shear stresses at the shock and, as a result, underpredicted the momentum losses incurred by the boundary layer.

There is some disagreement between the present calculations and the experiment as evident from Figs. 3 and 4; (1) the predicted Reynolds shear stresses are larger than the experimental stresses in the vicinity of the shock (x/c = 0.69 and 0.75), and (2) the predicted mean velocity recovery is less than the experiment downstream of reattachment. The former disagreement may be due to possible measurement errors in $(\overline{u'^2} - \overline{v'^2})$. At x/c = 0.69 and 0.75, the untransformed shear stresses were as large or slightly larger than the computed values. But, since the measured values

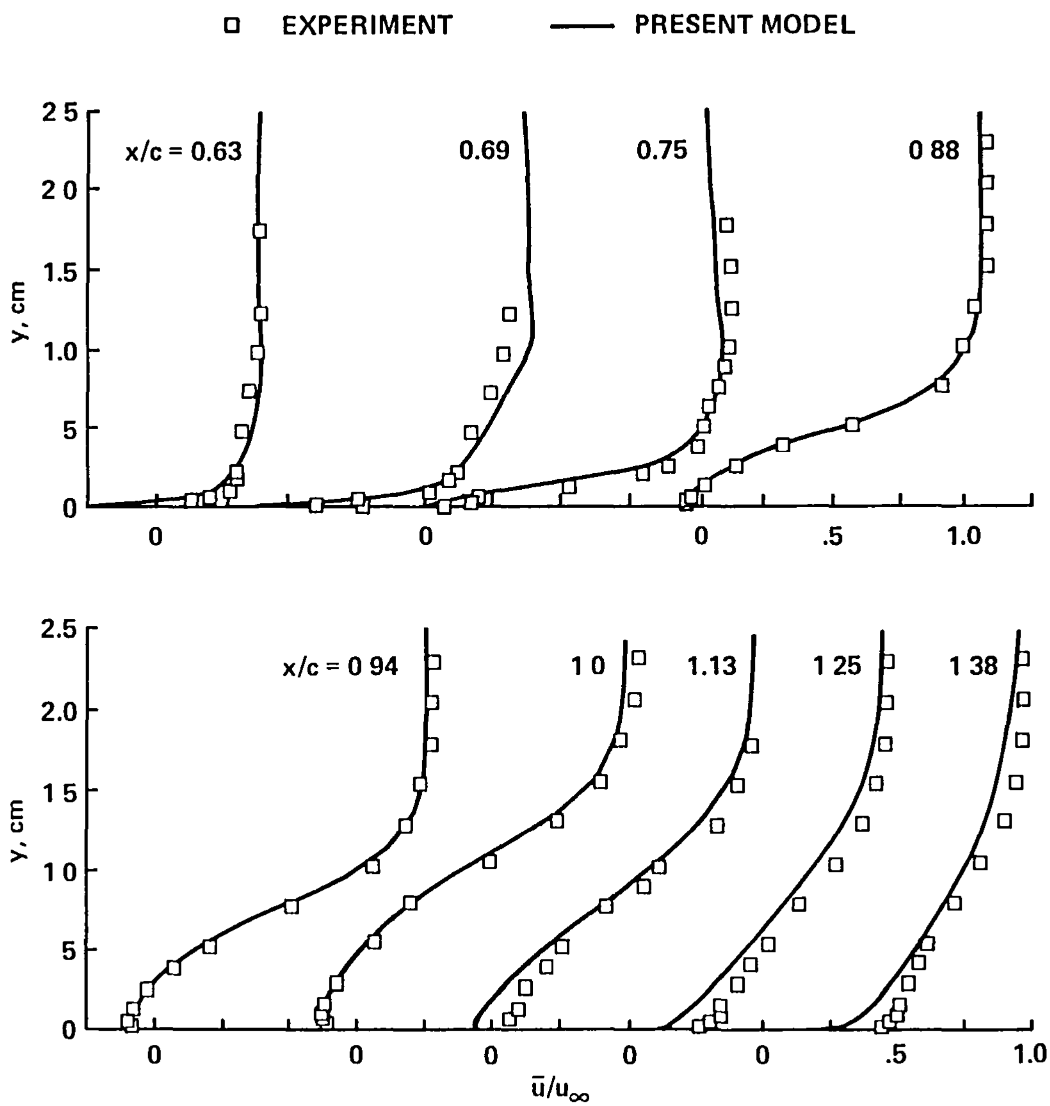

Fig.3. Mean-velocity comparisons for the axisymmetric-bump flow of Bachalo and Johnson [8]; M_∞ = 0.875.

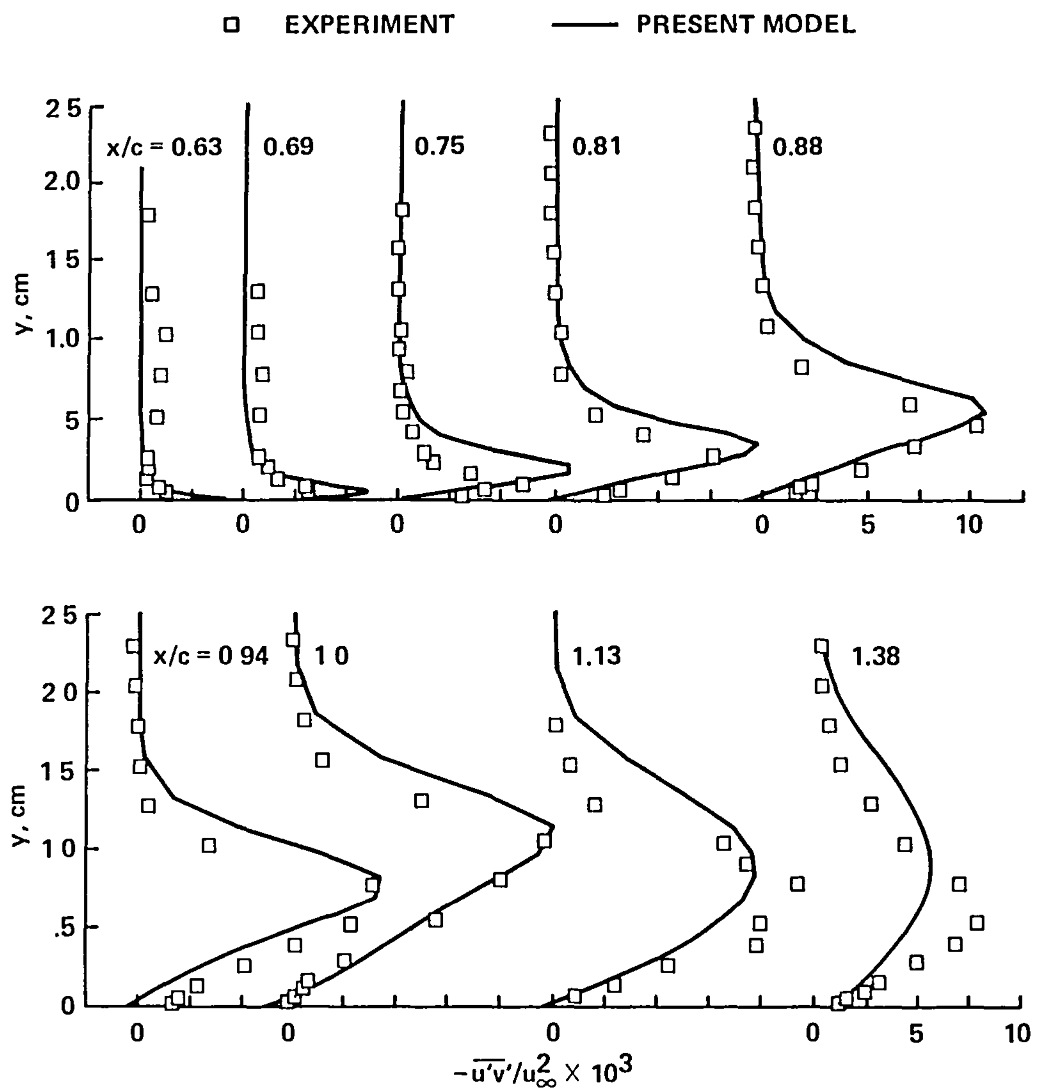

Fig.4. Reynolds shear-stress comparisons for the axisymmetric-bump flow of Bachalo and Johnson [8]; $M_\infty = 0.875$.

of $(\overline{u'^2} - \overline{v'^2})$ were so large in this region, a coordinate rotation of only a few degrees resulted in the much smaller shear stresses shown in Fig. 4. The latter disagreement downstream of reattachment appears to be a result of the actual inner length scales being larger than was modeled. The experimental eddy viscosity profiles suggest that the length scales in this region were closer to 0.8y than the 0.4y assumed in Eq. (2). (These discrepancies between the computations and the experiment are discussed in more detail in Ref. 5.)

The next two examples are transonic airfoil flows. Solutions for these flows were obtained using a Navier-Stokes airfoil code based on the algorithm of Beam and Warming [10]. The two examples are a supercritical airfoil (DSMA 671) section at transonic cruise conditions, and a NACA 64A010 airfoil section under shock-induced stall conditions. The experimental results for these two airfoils are given in Refs. 11 and 12, respectively. The calculations were performed at the set angles of attack with tunnel wall effects taken into account by using static pressure measurements at one chord above and below the airfoils as boundary conditions. The numerical details are given in Ref. 6.

In Fig. 5, predicted surface pressure distributions obtained with the Baldwin-Lomax [13] model and the present model for the supercritical airfoil case are compared with the experiment. The shock wave was weak and had little effect on the boundary layer, but the inviscid-viscous interaction near the airfoil trailing edge was quite strong. For example, the boundary-layer shape factor H grew to a value of 4 on the airfoil upper

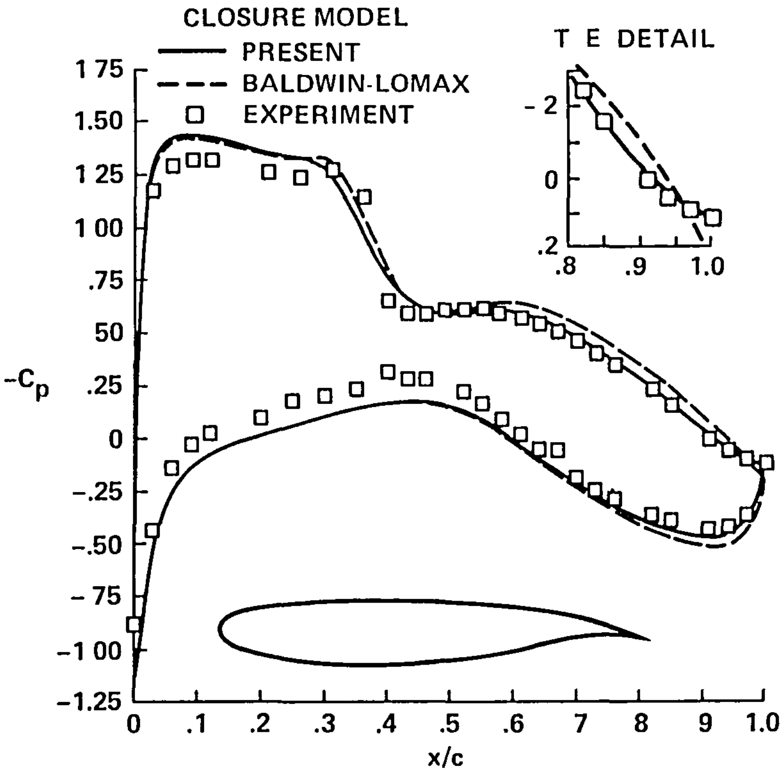

Fig.5. Surface pressure comparisons at $M_\infty = 0.72$ and $\alpha = 4.3°$ for the DSMA 671 supercritical airfoil section (data from Johnson and Spaid [11]).

surface (separation occurred at $x/c = 0.98$). The present model was better able to predict the observed rapid thickening of the boundary layer near the trailing edge than the Baldwin-Lomax model. As a consequence, the present model as seen in Fig. 5 gave better predictions of surface pressure on the rearward part of the airfoil. Notice that the present model was able to predict the pressure plateau just upstream of the trailing edge caused by boundary layer separation.

The last example is the NACA 64A010 at shock-induced stall conditions. In Fig. 6, predicted surface pressures are compared with the experiment. For this test case, a Cebeci-Smith model solution is shown since a steady solution could not be obtained with the Baldwin-Lomax model. As evident

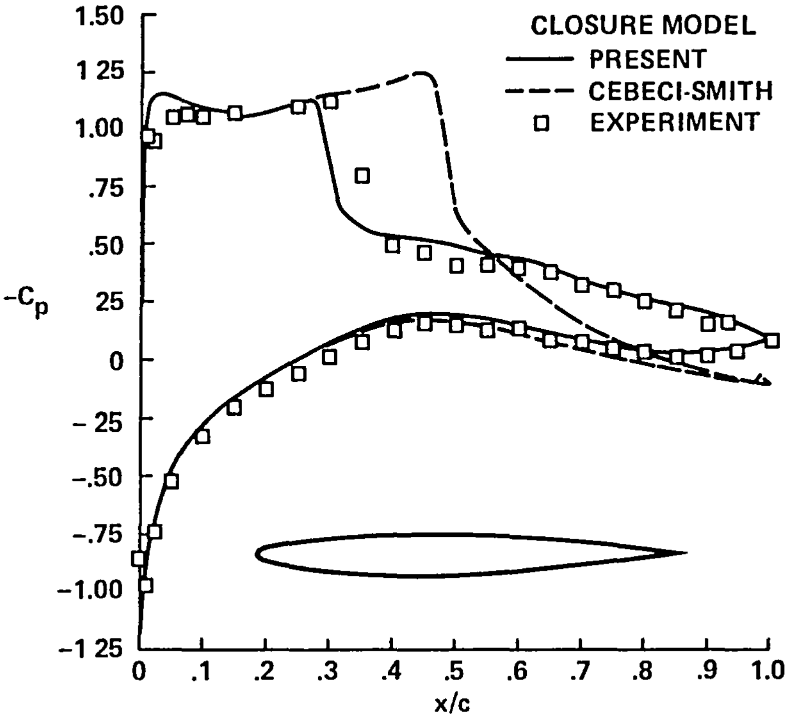

Fig.6. Surface pressure comparisons at $M_\infty = 0.8$ and $\alpha = 6.2°$ for the NACA 64A010 airfoil section (data from Johnson and Bachalo [12]).

from Fig. 6, the surface pressure distribution obtained with the present model is in substantially better agreement with the experiment than that obtained with the Cebeci-Smith model. In Fig. 7, predicted mean velocity and Reynolds shear stress profiles are compared with the experimental data in shear-layer coordinates. The predicted results based on the present model compare quite favorably with the experiment, especially considering the difficulty of this test case and the experimental uncertainties.

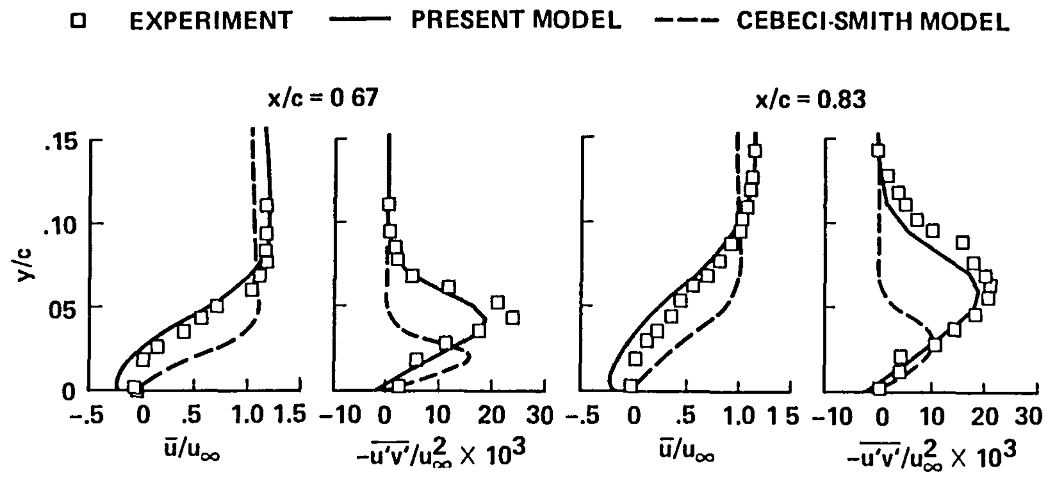

Fig.7. Mean-velocity and Reynolds shear stress comparisons at $M_\infty = 0.8$ and $\alpha = 6.2°$ for the NACA 64A010 airfoil section (data from Johnson and Bachalo [12]).

Concluding Remarks

As illustrated by the foregoing examples, a simple closure model has been developed which is capable of describing wall-bounded shear flows developing on airfoils at transonic conditions even when massive separation is present. The closure model requires little more computational effort than equilibrium algebraic closure models, and does not introduce any numerical stability problems.

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM 86826		

4. Title and Subtitle	5. Report Date
TRANSONIC SEPARATED FLOW PREDICTIONS BASED ON A MATHEMATICALLY SIMPLE, NONEQUILIBRIUM TURBULENCE CLOSURE MODEL	October 1985
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
D. A. Johnson and L. S. King	
	10. Work Unit No.
9. Performing Organization Name and Address	85390
Ames Research Center Moffett Field, CA 94035	11. Contract or Grant No.
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code 505-51-11

15. Supplementary Notes

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16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Transonic flow prediction Turbulence closure Separated flow	Unlimited Subject category - 34

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	13	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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